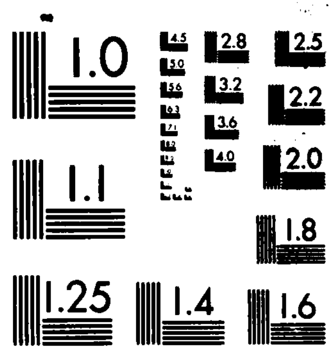
AD-A166 057 INTEGRATION OF DETECTORS WITH OPTICAL WAVEGUIDE STRUCTURES(U) CINCINNATI UNIV OH SOLID STATE ELECTRONICS LAB J T BOYD ET AL. 01 NOV 85 1/1

UNCLASIFIED AFOSR-TR-86-0099 AFOSR-81-0130 F/G 17/8 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFOSR-TR- 86-0099

(2)

Final Report

INTEGRATION OF DETECTORS WITH OPTICAL WAVEGUIDE STRUCTURES

J. T. Boyd and H. E. Jackson

Solid State Electronics Laboratory
Department of Electrical and Computer Engineering
University of Cincinnati
Cincinnati, Ohio 45221

J. T. Boyd, Principal Investigator

Prepared for the:

Air Force Office of Scientific Research

Grant AFOSR-81-0130

November 1, 1985

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE None	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 86-0099
6a. NAME OF PERFORMING ORGANIZATION University of Cincinnati 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Office of Scientific Research
6c. ADDRESS (City, State and ZIP Code) Department of Electrical & Computer Engrg. Mail Location #30 Cincinnati, OH 45221	7b. ADDRESS (City, State and ZIP Code) Bolling Air Force Base, D.C. 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Office of Scientific Research 8b. OFFICE SYMBOL (If applicable) NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-81-0130
8c. ADDRESS (City, State and ZIP Code) Bolling Air Force Base, D.C. 20332	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 61102F; PROJECT NO.: 2305; TASK NO.: B1; WORK UNIT NO.:
11. TITLE (Include Security Classification) Integration of Detectors and Optical Waveguide Structures	
12. PERSONAL AUTHOR(S) J.T. Boyd and H.E. Jackson	
13a. TYPE OF REPORT Final 13b. TIME COVERED FROM 3/15/81 TO 3/15/85	14. DATE OF REPORT (Yr., Mo., Day) 11/1/85 15. PAGE COUNT 33
16. SUPPLEMENTARY NOTATION	
17. COSATI CODES FIELD / GROUP / SUB. GR.	18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Photodetector, waveguides, recrystallization

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report summarizes results accomplished under the subject grant with many details appearing in other publications referenced in this report. Major accomplishments described occurred in three major areas. First, laser recrystallization of silicon was used to fabricate photodetectors having excellent performance directly on the surface of a planar optical waveguide. Photodetector reverse current values less than 10^{-12} amps, breakdown voltages of 60-80 V, and dynamic ranges of 55-60 dB were measured. Second, a new type of optical waveguide using SiO_2 was developed which was characterized by very low values of propagation loss. We measured values of loss as low as .06 dB/cm. Third, operation of a ring resonator formed using optical channel waveguides formed in SiO_2 was demonstrated and is described.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL ~~J. T. Boyd~~ Lt Col Robert Carter	22b. TELEPHONE NUMBER (Include Area Code) ~~513-475-3066/4461~~ 202 767-4931 22c. OFFICE SYMBOL NE

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

Table of Contents

I. Introduction

The present report describes the accomplishments of the grant AFOSR 81-0130 entitled "Integration of Detectors With Optical Waveguide Structures." Most of the important results have been published (See Section VI for a list of Program publications) so the present report does not contain full detail of all accomplishments. For those wishing more detail in a certain area, specific publications will be referenced throughout this report. It is noteworthy that 15 journal papers, 11 conference presentations with written proceedings, 9 conference presentations with no written proceedings, 5 Ph.D. dissertations, and 3 M.S. theses resulted from research either fully supported by or partially supported by this grant.

Major accomplishments supported by this grant occurred in three areas: (1) integration of photodetectors having high performance formed using laser recrystallization onto optical waveguide surfaces,[1,2] (2) formation of very low loss planar SiO_2 waveguides,[3,4] and (3) demonstration of ring resonator operation utilizing SiO_2 optical waveguides.[5] In what follows we shall consider the above topics in some detail along with the results of several related investigations. Specifically, we shall also describe our demonstration of enhanced quantum efficiency in silicon photodetectors at GaAlAs laser wavelengths,[6] and our demonstration of a new sensor element for CCD imaging arrays which provides a logarithmic response over a range of seven decades.[7] As a part of the study of the log-converting sensing element, we developed a novel metal-oxide-

semiconductor field effect transistor (MOSFET) utilizing three gates which provides independent control of transconductance and output resistance.[8]

To support the overall goals of Air Force research, there has been significant interaction between personal involved in the present and past AFOSR research program and those involved in military programs at the Air Force Avionics Laboratory, Rockwell International, McDonnell-Douglas, Battelle, Motorola, General Dynamics, Lockheed, Honeywell, and Oak Ridge National Laboratory. A number of papers have been co-authored by personnel from several of these institutions with personnel from the Solid State Electronics Laboratory at the University of Cincinnati.

The focal plane disector is a device structure which was originally conceived and first demonstrated by D. A. Ramey and J. T. Boyd of the University of Cincinnati working under AFOSR funding.[9,10] This concept is now being contracted by the Air Force Wright Aeronautical Laboratories (Avionics Laboratory) to the Westinghouse Defense Electronics Center for development and use in optical signal processing systems.

II. Photodetectors

In this section we consider several aspects of research involving photodetection. We consider first the formation of photodetectors with very good performance in laser recrystallized silicon formed from polysilicon which had been previously deposited onto an optical waveguide surface. These photodetectors are formed in silicon layers which are about .5 microns thick. Such thin layers are normally not effective as detectors, but for our structure the thin photodetectors are quite effective for optical waveguide detection because edge illumination is used. We present later in this section experimental data illustrating the enhanced quantum efficiency one can obtain by using edge illumination. Finally, we describe the concept of a log-converting photodetector sensor element suitable for incorporation into linear charge coupled device (CCD) image array.

A. Photodetector Formed in Laser Recrystallized Silicon

We have demonstrated integrated detection of light propagating in an optical waveguide with a photodetector array fabricated directly on the waveguide surface.[1,2] Polycrystalline silicon was first deposited and then laser recrystallized. The presence of grain boundaries in the recrystallized silicon is confined to specific locations by using a pattern of anti-reflection coatings.[11] In our case a 650A layer of Si_3N_4 was deposited on the oxide-covered polysilicon and lithographically patterned to form a periodic array (28 micron period) of 8 micron wide anti-reflection stripes. An argon ion laser with an output power of 9-11 watts illuminates a layer of 0.45 micron thick LPCVD polysilicon capped with a 150A layer of SiO_2 and is scanned at a

velocity of 20 cm/sec unidirectionally parallel to the anti-reflection stripes. The focused spot of the laser is 55 microns with a scan-to-scan spacing of 17 microns. Because more laser power is transmitted through the anti-reflection stripes, those regions are heated to a higher temperature so that recrystallization begins midway between the anti-reflection stripes. Grain boundaries thus become localized along the anti-reflection stripes where two adjacent regions undergoing recrystallization meet.

By optimizing exposure parameters, multiple adjacent single crystal regions each 20 microns wide and several millimeters long have been formed with grain boundaries in between. Because these single crystal regions are periodically spaced, they are ideal for fabrication of a photodetector array where one photodetector is positioned in the center of each single crystal region. The periodic spacing of the photodetector array is thus the same as that of the anti-reflection stripes. The grain boundaries then lie in the isolation region between adjacent photodetector elements; these regions are removed by plasma etching after junction formation to eliminate any adverse effect the presence of the grain boundary might have on electrical crosstalk.

Figure 1 shows a cross-sectional view in a plane normal to the array axis of one element of the complete integrated waveguide structure. The 0.14 micron Si_3N_4 waveguide is deposited by LPCVD on a 1.6 micron SiO_2 layer thermally grown on a silicon substrate. The photodiode structure was fabricated by ion implantation with boron, boron, and phosphorus doses of 3×10^{14} cm^{-2}, 6×10^{11} cm^{-2}, and

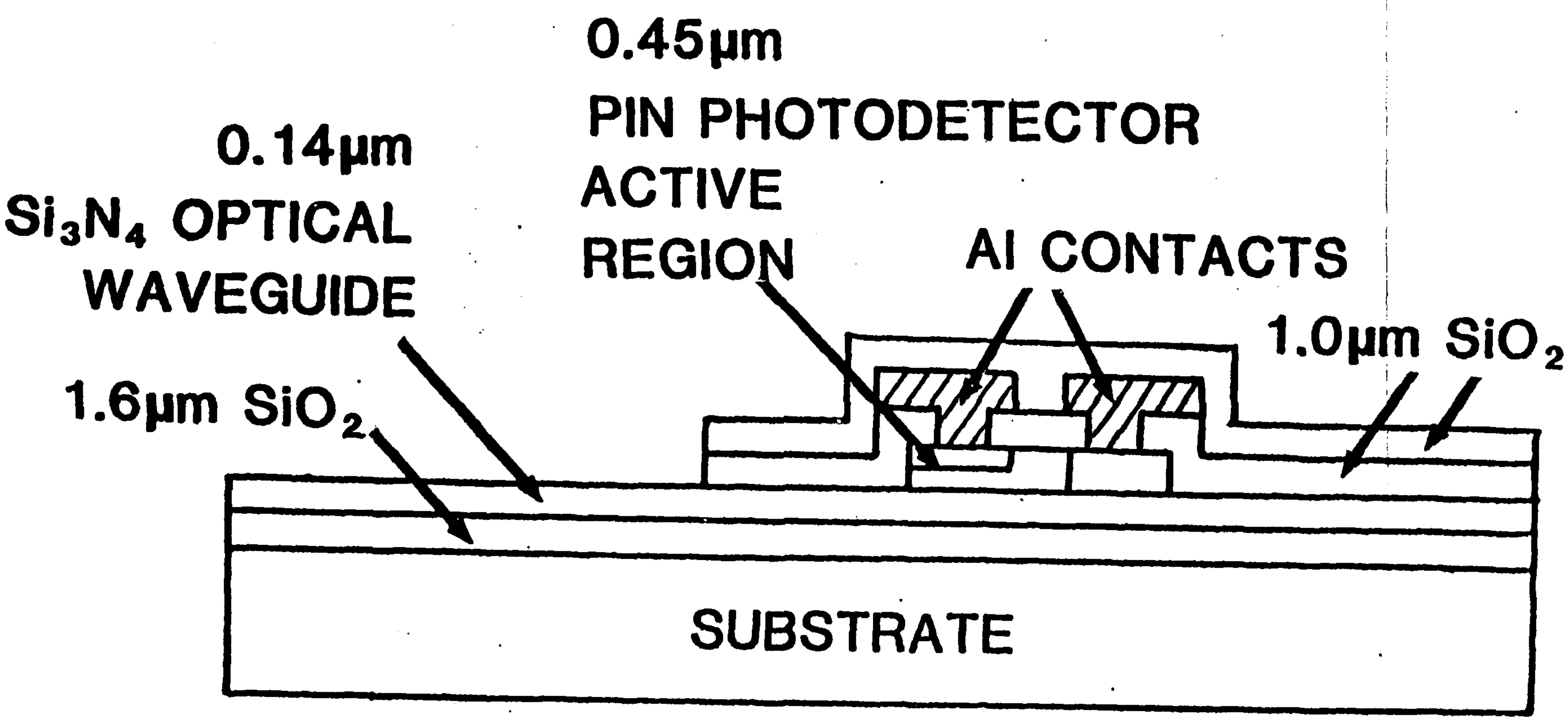


Figure 1. A cross-sectional view of one element of the integrated optical photodetector array fabricated on a planar Si_3N_4 optical waveguide.

1×10^{15} cm^{-2}, and energies of 40 keV, 60 keV, and 150 keV for the p+, p-and n+ implants, respectively. The photodetectors here are edge-illuminated so that the quantum efficiency is determined by the length of the photodetector normal to the array axis. As this dimension does not effect array resolution, i.e. corresponds to the long dimension of the crystalline grains, it can be sufficiently long to yield high values of quantum efficiency due to edge illumination.

In Fig. 2 we compare the current-voltage characteristics of photodiodes formed in non-recrystallized polysilicon (solid curves) with those formed in laser recrystallized silicon (dashed curves). Several curves are displayed for different values of d, the separation between the p+ and n+ regions. Note that a high reverse leakage current and a soft breakdown are observed for the photodiodes formed on polysilicon. In contrast, for the photodiodes formed on laser recrystallized silicon much lower leakage currents (in the 10^{-12} amp range) and a sharper breakdown characteristic with breakdown voltages of about 50 volts are observed. The low leakage currents observed here are about 3 orders of magnitude smaller than those previously reported[12] for a lateral diode formed in laser recrystallized silicon, and correspond to leakage current densities somewhat less than the 10^{-5} amp/cm^2 previously reported.[12]

In order to demonstrate integrated waveguide detection by the photodetectors, light from a 4 mW He-Ne laser operating at 632.8 nm was prism-coupled into the Si_3N_4 waveguide and thus to a photodetector element. The I-V curves in Fig. 3 show the detector response in the presence of light in the waveguide (dashed curves) and well as the

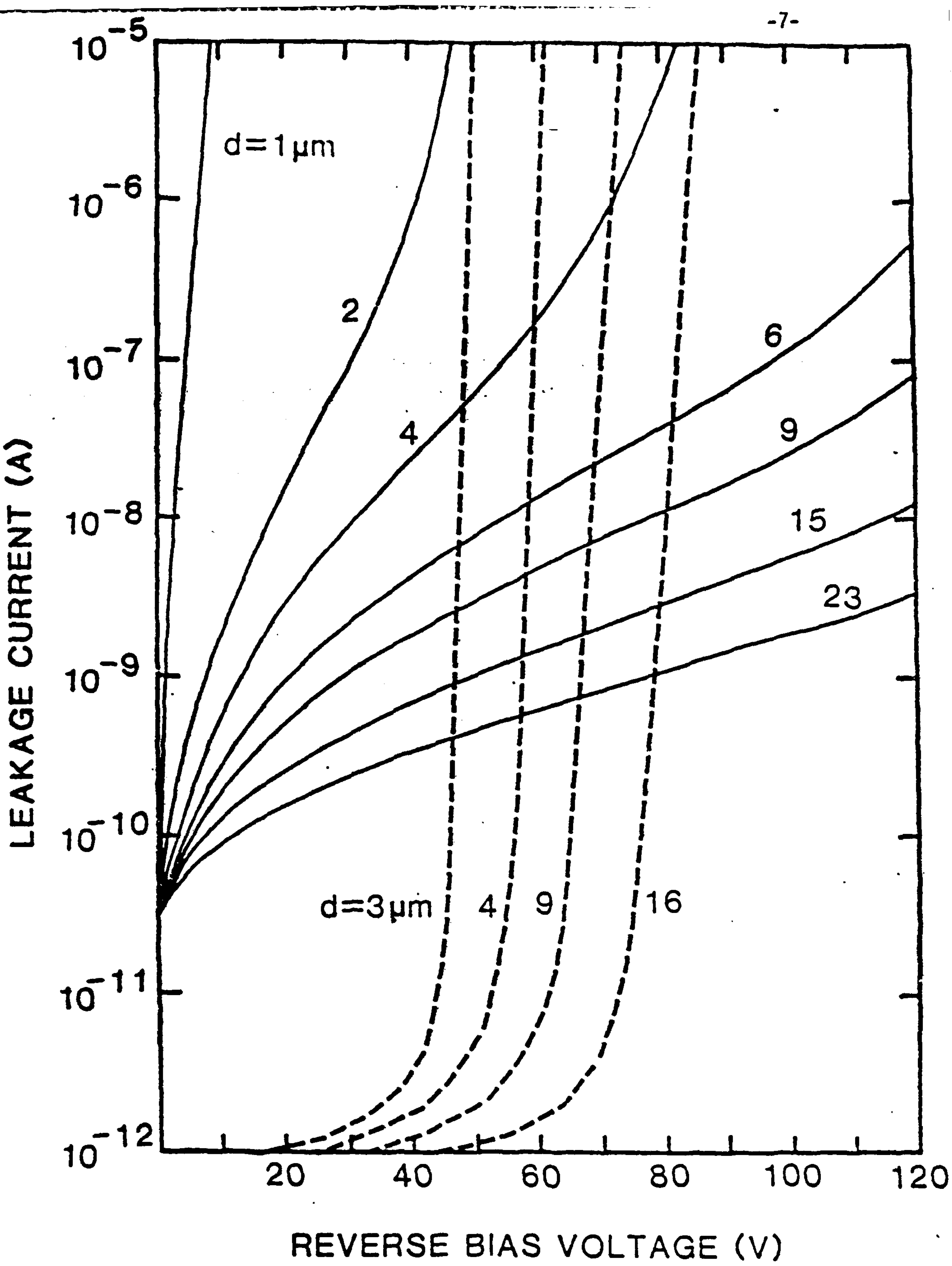


Figure 2. Comparison of current-voltage characteristics of photodiodes formed in non-recrystallized polysilicon (solid curves) and photodiodes formed in laser recrystallized silicon (dashed curves). Curves are given for several values of d, the spacing between the p+ and n+ regions.

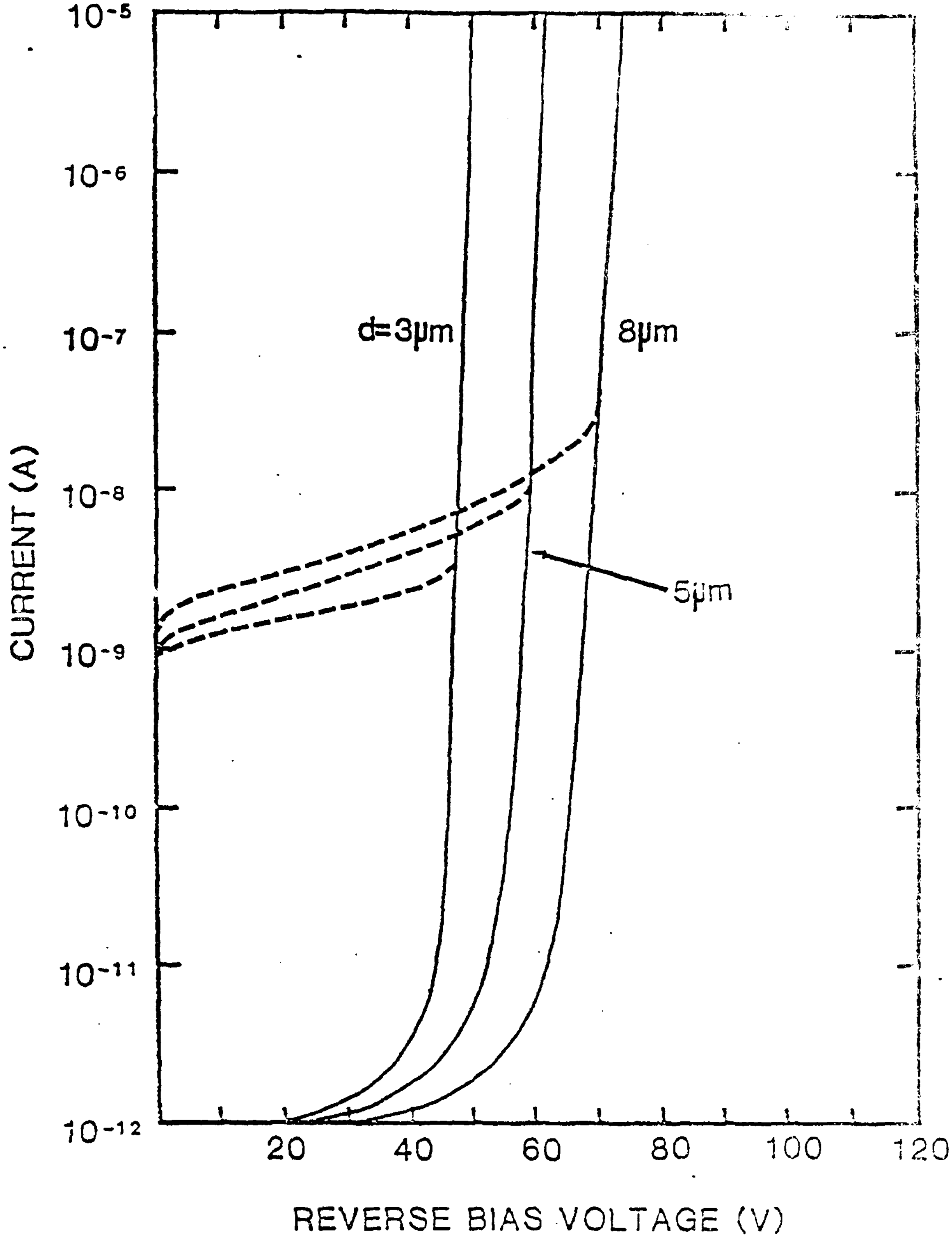


Figure 3 Current-voltage characteristics of an element of the photodetector array formed on recrystallized silicon with light propagating in the waveguide (dashed curves) and without light propagating in the waveguide (solid curves). Detection of light from the waveguide provides a photocurrent response of 3-4 orders of magnitude for a input He-Ne laser power of 1 mW.

response in the absence of light in the waveguide (solid curves). Integrated waveguide detection is demonstrated by these curves which show a three order of magnitude increase in current when light is present in the waveguide. Figure 4 displays the optical dynamic range observed for several photodetectors. The dynamic range was measured to be 55 dB for d=5 microns, increasing to 60 dB for a device with d=27 microns.

B. Enhanced Quantum Efficiency by Edge Illumination

We experimentally investigated the concept of illuminating a silicon photodetector along an edge to increase the light propagation path through the depletion region and thus to increase quantum efficiency at near IR wavelengths.[6] Quantum efficiency measurements using both a GaAlAs laser and a He-Ne laser were performed. These measurements show an improvement in quantum efficiency at a wavelength of 0.83 microns for edge illumination over normal incidence of 75% for a photodiode and of 142% for a MOS capacitor photosensor.

Table I lists the results of the quantum efficiency measurements performed on both photodiode and MOS capacitor sensors at both laser wavelengths for edge illumination and normal incidence. As expected, we see a significant improvement by using edge illumination for both types of photosensors at a wavelength of 0.83 microns in comparison to normal incidence. In contrast little change in quantum efficiency at the wavelength of 0.63 microns is seen for the two methods of illumination for the photodiode. The measurements reported in Table I indicate that edge illumination has an additional advantage for use with the MOS capacitor photodetector. The data indicates that for

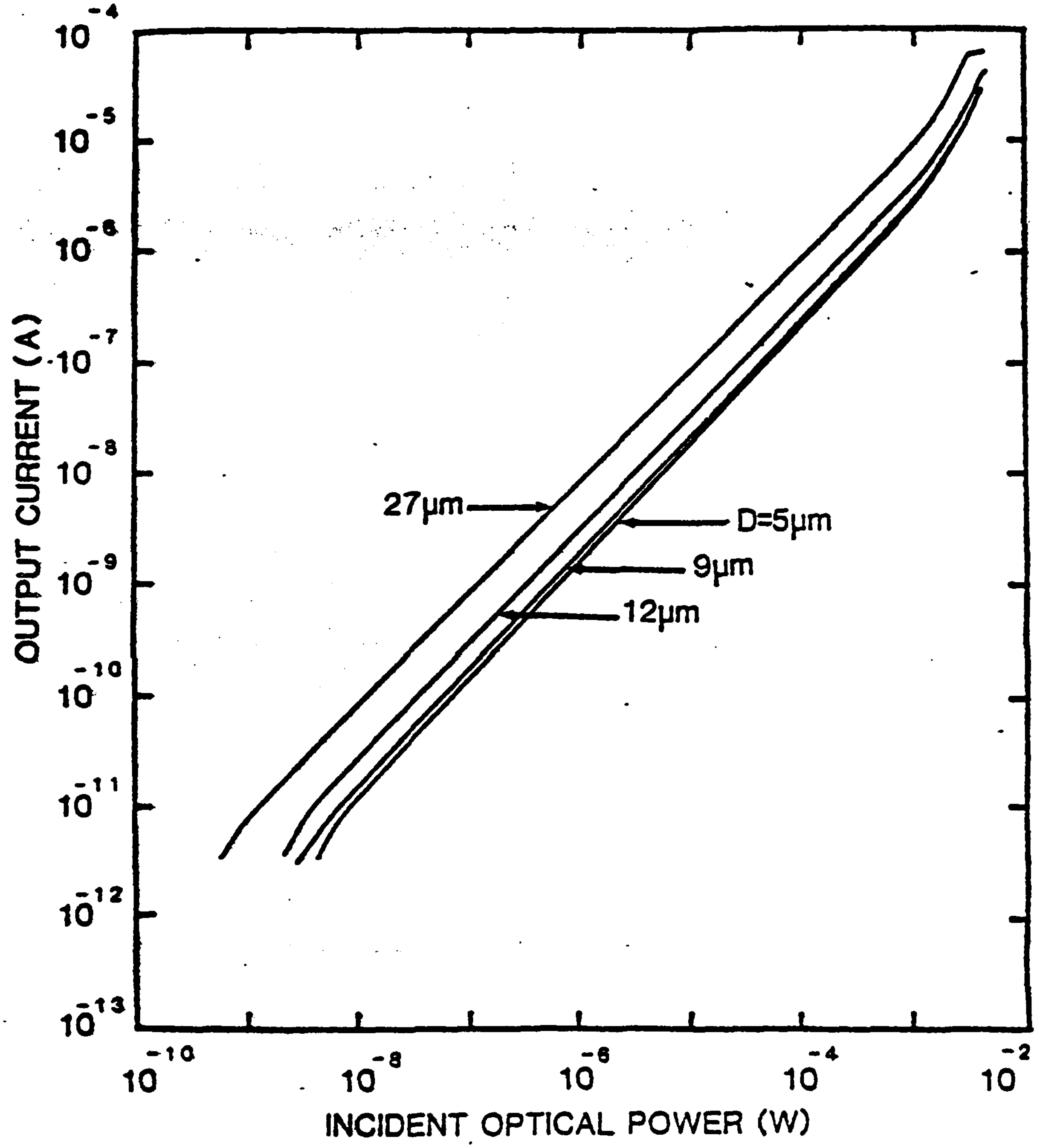


Figure 4. Plot of detector output current as function of incident laser power for several values of d.

TABLE I

Quantum efficiency obtained for different cases

	Quantum Efficiency					
	Photodiode			MOS Capacitor		
	Edge Illumination	Normal Incidence	% of Increase	Edge Illumination	Normal Incidence	% of Increase
$\lambda = 0.83\ \mu m$	0.63	0.36	75%	0.63	0.26	142%
$\lambda = 0.63\ \mu m$	0.63	0.60	5%	0.63	0.31	103%

this photosensor element, edge illumination provides improvement in quantum efficiency for visible radiation. For this case the use of edge illumination avoids the loss of light in the polysilicon gate and that due to multiple reflections occurring in the multilayer MOS structure associated with normal incidence. We would expect that this quantum efficiency enhancement associated with edge illumination would be even greater in the blue region of the spectrum because of the large absorption of polysilicon in this region.

C. Log-Converting CCD Sensor Element and Three-Gate MOSFET

A photosensor element suitable for incorporation into charge-coupled device (CCD) imaging arrays in which the charge injected into the CCD is proportional to the logarithm of incident light intensity has been experimentally demonstrated.[7] The photosensor element consists of a photodiode directly coupled to a two-stage MOSFET common source amplifier. This element occupies an area of 25 X 100 microns and is arranged so that it could be incorporated into a linear CCD imaging array having a period of 25 microns. A logarithmic response is measured over a 68.6 dB range of incident light intensity with a sensitivity of 55 mV/decade of light intensity. Both the theory of operation and the design of the test structure are included in our published paper on this subject.[7]

As a part of this study we considered the possibility of using a three-gate MOS transistor. We fabricated such a device using overlapping polysilicon gate technology and demonstrated operation.[8] Measurements of operating characteristics illustrate the availability of excellent control of the transconductance while simultaneously

maintaining very high output resistance. In analog circuit applications, the three-gate device provides additional advantages including better signal isolation, less nonlinearity, and adjustable mismatch in a differential amplifier. A range of operating voltages over which the transconductance is constant was reported in our paper.[8]

III. Optical Waveguides Formed in SiO_2

We began this investigation by fabricating thick layers of SiO_2 and examining their waveguiding characteristics. In 1982 we fabricated waveguides from thick layers of SiO_2 and carried out loss measurements on the samples.[13] For an oxide thickness of 15 microns the loss was less than 1 dB/cm for a thermally grown oxide on Si. In spite of this rather large value of loss, the amount of out-of-plane scattering observed was extremely low, with the normally observed streak essentially invisible. The dominant contribution of loss was thus considered to be due to coupling and absorption by the Si substrate instead of scattering. To eliminate this substrate loss, stronger field confinement is needed.

Phosphorus doping was then used in an attempt to provide stronger field confinement since its presence increases the refractive index of SiO_2. Stronger field confinement was observed in that losses of about 1 dB/cm were observed for smaller total oxide thicknesses of about 6 microns. It was difficult to separate the effect of the doping of the oxide from strain and relaxation effects. Also, to achieve the theoretical index change, much higher impurity concentrations than were initially used in the experiment would be required.

Following this some, effort was directed towards oxidizing silicon under time varying conditions, as the refractive index of the oxidized layer varies with temperature and ambient. We did not obtain much in the way of encouraging results here, but the results we did obtain have been published.[14]

Recently, low loss planar optical waveguides have been fabricated by thermal nitridation of thick silicon dioxide films.[3,4] The waveguides were formed by oxidizing silicon wafers at 1100°C in steam and then exposing them to an atmosphere of electronic grade ammonia in the same furnace tube and at the same temperature for periods between one and ten days. Measurements of waveguide loss, effective refractive index and refractive index were performed as functions of nitridation time for nine samples. Losses for these samples ranged between 0.06 and 0.31 dB/cm and generally decreased with increasing nitridation time. The sliding prism method with three prism correction was used to measure loss. Loss measurement data for the samples having the lowest loss, the highest loss, and an intermediate value are shown in Figure 5.

The refractive index obtained from ellipsometry, assuming a homogeneous oxynitride film on SiO_2, ranged from 1.67 to 1.74. As waveguide effective refractive indices were measured to be about 1.47, we concluded that the oxynitride layers were on the order of 100 nm and that the single allowed mode was loosely confined.

Auger electron spectroscopy was used to characterize our nitridation process. The nitrogen concentration profile determined from these measurements for a 275 nm thick oxide layer is shown in Figure 6. The nitrogen concentration decreases rapidly with depth near the oxide surface and then remains nearly constant except in a region near the Si-SiO_2 interface. Here, the Auger data show a peak in the nitrogen concentration similar to that observed by others.

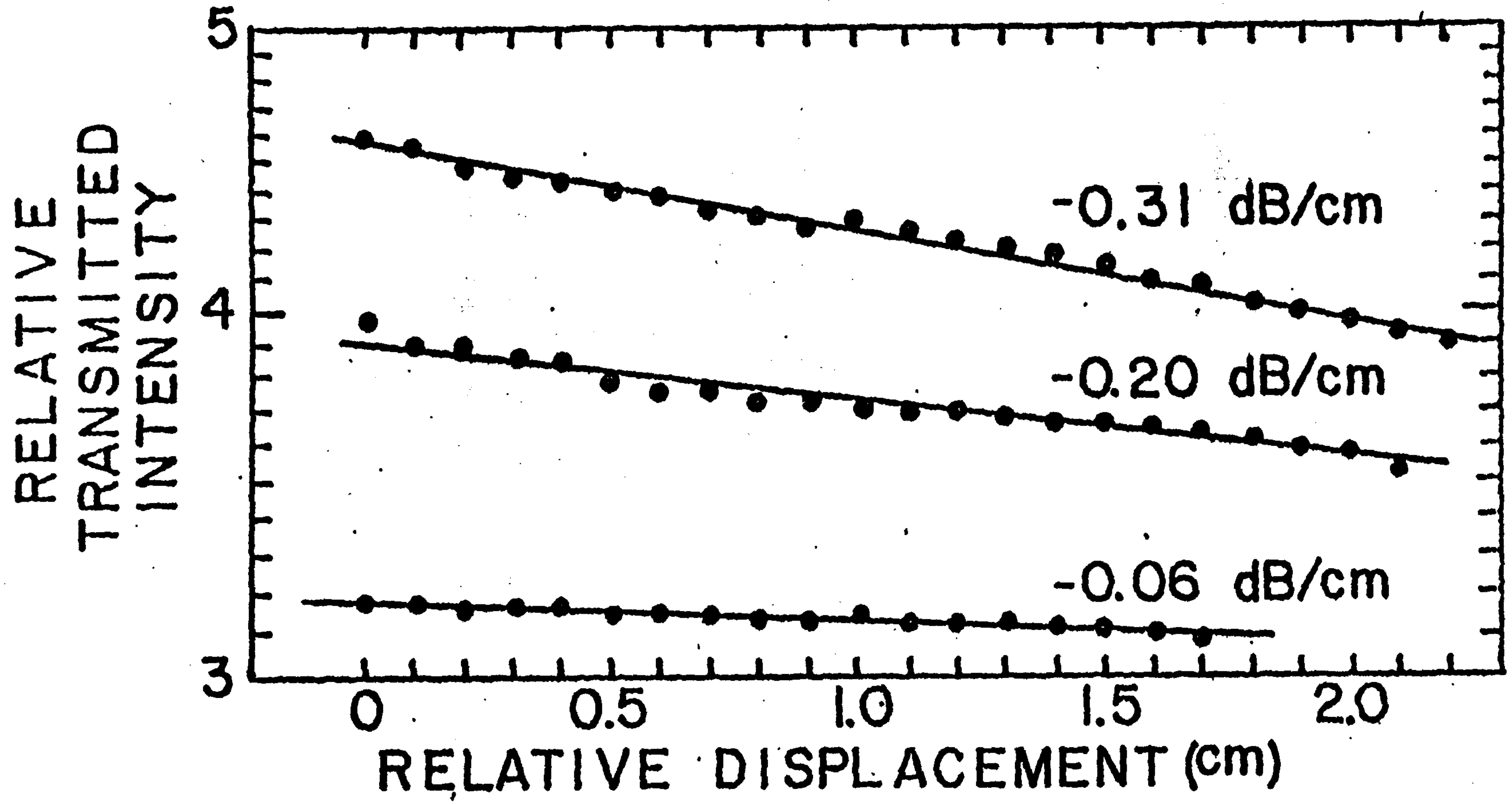


Figure 5. Logarithm of the relative transmitted intensity is plotted vs position of the output prism along the waveguide. The straight line represents a least squares fit to the data. The intensities plotted for each of three cases have been normalized independently.

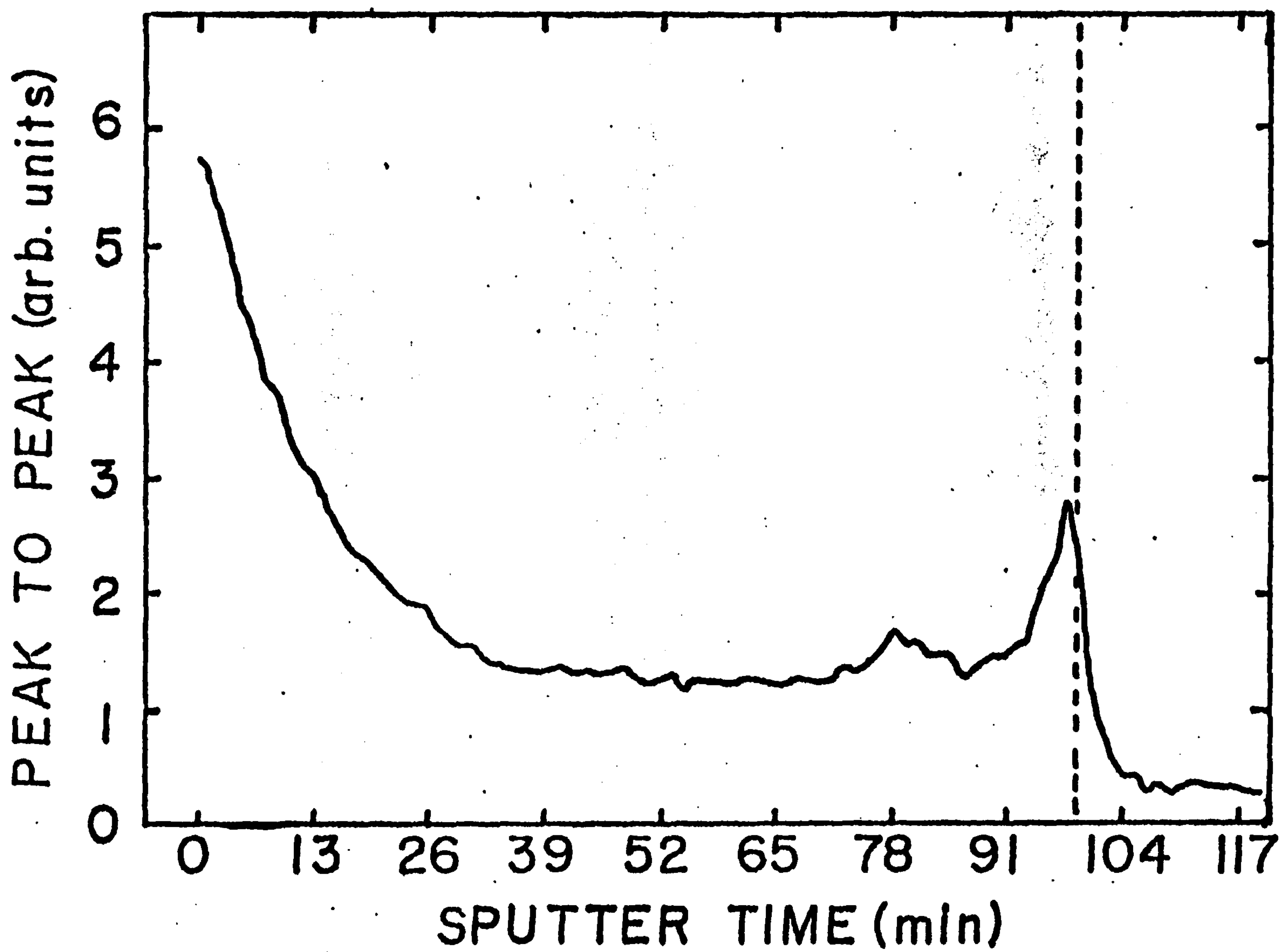


Figure 6. Depth profile measured by Auger electron spectroscopy of a 275 nm thick SiO_2 film nitrided at 1100°C in electronic grade ammonia for 5 days. The dotted line indicates the Si-SiO_2 interface.

IV. Ring Resonators Formed in Phosphosilicate Glass Optical Channel Waveguides

We have presented the design philosophy for a ring resonator fabricated in phosphosilicate glass (PSG) films elsewhere.[5,15] Here we will summarize some of the results. The closed loop resonator was fabricated in phosphosilicate glass films deposited by chemical vapor deposition onto oxidized silicon substrates. A channel waveguide-to-channel waveguide tapered mode directional coupler was used to transfer light from the input channel to the ring. To our knowledge this is the first demonstration of the use of such a coupler for coupling between channel waveguides. An analysis is presented elsewhere for power distribution in the channels of the coupler, for stored, reflected and transmitted powers in the resonator and for resonator finesse. Operation of the resonator was demonstrated experimentally and finesse values of less than 3, comparable to those published elsewhere in the literature, were obtained.

Our design for the resonator was constrained by practical considerations and did not necessarily represent an ideal design based on theory. Nonetheless it proved to be effective in producing working devices. For the closed loop that forms the resonant structure we used a racetrack configuration with lengths ranging from 8 to 16 mm. The radii of curvature of the arcs were either 2 or 3 mm. We had determined that for channel widths and refractive indices that we were using, these radii would ensure curvature radiation losses much less than 0.5 db for 2π radians. Racetrack channel widths on different devices ranged from 4 to 7 microns. Input channel widths

were tapered from about 2 microns greater than the racetrack channel width at one end to 2 microns smaller at the other. A slab region was provided for prism coupling light into the waveguides. A 3 mm long horn tapering from 110 microns to the channel-end width provided the transition between slab and channel guides. Mode vector values were calculated using equations for channel waveguides. For the tapered channels we calculated mode vector values at different cross-sections, assuming in the spirit of local normal mode theory that we could use the same expressions as those for a uniform channel having the same width as that at the cross-section. This leads to a dependence on distance, for the function representing the propagation vector difference between the two channels, which cannot be expressed in a simple form. However for the ranges of channel widths and coupler lengths that we used the difference function can be considered to vary approximately linearly with distance.

To test the resonators we coupled laser light into the slab portion of the waveguide using a prism. The guided beam entered the channels from the slab section via a horn shaped transition region. Since the directional coupler was formed from two ridge waveguides with a 3 microns air gap between them, there was negligible coupling between the two channels. In order to enhance coupling we placed a drop of index-matching fluid (of refractive index 1.462) over the channels so as to fill the gap. The refractive index of the PSG ranges roughly from 1.465 to 1.47 at phosphorus concentrations around 7-10 wt. %, consequently we do not think that the guides "merged" together. This is supported by the observation that the guides could

be distinguished beneath the fluid which would not have been the case had the indices of the two been the same. The resonator was driven through its extrema by heating with a hot nitrogen stream.

As the resonator was heated and then allowed to cool, periodic variations in the intensity of output light were recorded. Figure 7 shows a trace of output light intensity for resonator #N91A. The first portion of the trace was recorded with no index-matching liquid present in the coupler region. As is evident, heating and cooling has no effect on the light level because no light was coupled into the racetrack. When index-matching liquid was used to cover the waveguides in the coupler region the output intensity increased. The reason for this increase is that the liquid also acts as a cladding layer for the ridges and reduces scattering losses from surface defects. In the presence of index-matching liquid, heating and cooling the device produces unambiguous variations in output intensity indicating that light coupled into the racetrack went through constructive and destructive interferences as the thermal stimulus caused dimensional and refractive index changes in the waveguide.

Operation in other samples was also demonstrated with the results presented elsewhere.[5,15] There we also present a discussion of how finesse is interpreted from data such as that in Figure 7.

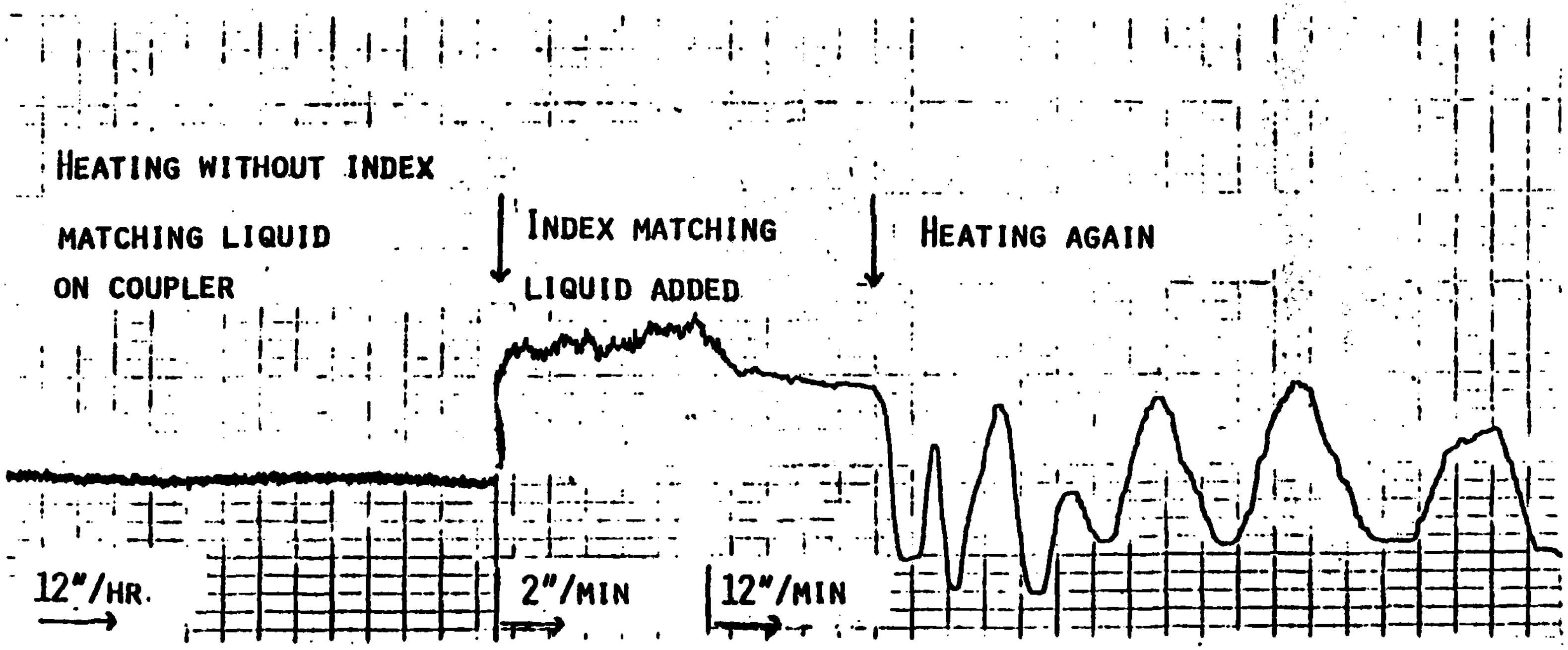


Figure 7. Experimentally recorded response of resonator N91A as a function of time.

V. Summary and Conclusions

A significant amount of research has been performed as a part of this research program supported by AFOSR. The main results have been discussed here with many additional details appearing in other publications listed in section VI. It is noteworthy that we have demonstrated integration of a detector onto an optical waveguide surface. Polycrystalline silicon was first deposited and then laser recrystallized to form large periodic grains within which photodetectors were formed. Because the device area was within a single crystalline grain, excellent junction and light detection performance was obtained.

By forming photodetectors on the waveguide surface, these photodetectors were illuminated by light propagating in the waveguide from their edge. We showed that this concept of edge illumination could significantly enhance the quantum efficiency of silicon photodetectors illuminated by light at the GaAlAs laser wavelengths.

In the area of SiO_2 waveguides we have shown that low loss planar waveguides could be formed using thermal nitridation. At the same time we demonstrated operation of a ring resonator using phosphorus-doped SiO_2. The resonant performance of this device was limited due to the rather high loss of the phosphorus-doped channel waveguides. Thus, if we can develop a low loss channel waveguide based on thermal nitridation, then we could make a ring resonator having much better performance.

In some light detection applications a wide range of light levels can be incident on a senor element of a photodetector array. For such situations we have developed a log-converting sensor element suitable for incorporation into a liner CCD imaging array and demonstrated operation.

VI. List of Program Publications: AFOSR 81-0130

Journal Papers

A. Naumaan and J.T. Boyd, "Ring Resonator Fabricated in Phosphosilicate Glass Films Deposited by Chemical Vapor Deposition," submitted for publication.

D.E. Zelmon, J.T. Boyd, and H.E. Jackson, "Low Loss Optical Waveguides Fabricated by Thermal Nitridation," Applied Physics Letters, accepted for publication.

J.T. Boyd, R.W. Wu, D.E. Zelmon, A. Naumaan, H.A. Timlin, and H.E. Jackson, "Guided Wave Optical Structures Utilizing Silicon," Optical Engineering, Special Issue on Integrated Optical Circuit Engineering, Vol. 24, pp. 230-234, 1985.

R.W. Wu, J.T. Boyd, H.A. Timlin, Howard E. Jackson, and John L. Janning, "Optical Waveguide Detection: Photodetector Array Formed on the Waveguide Utilizing Laser Recrystallized Silicon," Applied Physics Letters, Vol. 46, pp. 498-500, 1985.

S.H. Chang and J.T. Boyd, "Log-Converting Processor Element for CCD Linear Imaging Arrays," Applied Optics, Vol. 22, pp. 3569-3571, 1983.

S.H. Chang, J.T. Boyd, and J.H. Nevin, "Three Gate MOSFET Providing Independent Control of Transconductance and Output Resistance," IEEE Electron Device Letters, Vol. EDL-4, pp. 289-291, 1983.

C.L. Fan and J.T. Boyd, "Improvement in the Quantum Efficiency of Silicon Photodetectors at Near IR Wavelengths by Edge Illumination," Applied Optics, Vol. 22, pp. 3297-3299, 1983.

D.E. Zelmon, H.E. Jackson, J.T. Boyd, A. Naumaan, and D.B. Anderson, "A Low-Scattering Graded-Index SiO_2 Planar Optical Waveguide Thermally Grown on Silicon," Applied Physics Letters, Vol. 42, pp. 565-566, April 1, 1983.

S. Dutta, H.E. Jackson, J.T. Boyd, and C.W. White, "Rutherford Back Scattering (RBS) Evidence for Solid Phase Laser Annealing of Corning 7059 Glass and ZnO Thin Films," Journal of Applied Physics, Vol. 54, pp. 2125-2126, April, 1983.

S. Dutta, H.E. Jackson, and J.T. Boyd, "Use of Laser Annealing to Achieve Low Loss in Corning 7059 Glass, ZnO, Si_3N_4, Nb_2O_5, and Ta_2O_5 Optical Thin Film Waveguides," Optical Engineering, Vol. 22, pp. 117-120, January, 1983.

S. Dutta, H.E. Jackson, J.T. Boyd, R.L. Davis, and F.S. Hickernell, "CO_2 Laser Annealing of Si_3N_4, Nb_2O_5, and Ta_2O_5 Thin Film Waveguides to Reduce Optical Scattering," IEEE Journal of Quantum Electronics, Vol. QE-18, pp. 800-806, April, 1982, Joint Special Issue on Optical Guided Wave Technology, also published in IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-30, April, 1982.

J.T. Boyd, S. Dutta, H.E. Jackson, and A. Naumaan, "Reduction of the Effects of Scattering by Laser Annealing of Optical Waveguides and by Use of Integrated Waveguide Detection," Optical Engineering, Vol. 21, pp. 293-295, 1982.

J.T. Boyd, S. Dutta, H.E. Jackson, and A. Naumaan, "Reduction of the Effects of Scattering by Laser Annealing of Optical Waveguides and by Use of Integrated Waveguide Detection," Optical Engineering, Vol. 21, pp. 293-295, 1982.

F.K. Hopkins, H.E. Jackson, and J.T. Boyd, "In-Plane Scattering Measurements in a Planar Optical Waveguide by an Integrated Technique," Applied Optics, Vol. 20, pp. 2761-2763, Aug. 15, 1981.

S. Dutta, H.E. Jackson, J.T. Boyd, F.S. Hickernell and R.L. Davis, "Scattering Loss Reduction in ZnO Optical Waveguides by Laser Annealing," Applied Physics Letters, Vol. 39, pp. 206-208, Aug. 1, 1981.

Conference Presentations With Written Proceedings

D.E. Zelmon, H.E. Jackson, and J.T. Boyd, "Use of Thermal Nitridation to Fabricate Low Loss Planar Optical Waveguides in SiO_2," to be presented at and published in The Proceedings of the Second SPIE International Conference on Integrated Optical Circuit Engineering, Cambridge, MA, September, 1985.

J.T. Boyd, H.E. Jackson, D.E. Zelmon, and R.W. Wu, "Low Loss SiO_2 Optical Waveguides Formed By Thermal Nitridation and Photodetectors Formed on Waveguide Surfaces Utilizing Laser Recrystallized Silicon," presented at and published in The Proceedings of the 1985 National Science Foundation Grantee-User Meeting on Optical Communications, Cornell University, June, 1985.

H.E. Jackson and J.T. Boyd, "Low Loss Thin Film Materials For Integrated Optics," presented at and published in The Proceedings of the American Physical Society Topical Meeting on Basic Properties of Optical Materials, May, 1985.

R.W. Wu, H.A. Timlin, H.E. Jackson, and J.T. Boyd, "Photodetector Arrays in Laser Recrystallized Silicon Integrated With an Optical Waveguide," presented at and published in The Proceedings of the Materials Research Society Meeting, Boston, November, 1984.

J.T. Boyd, "Planar and Channel Optical Waveguides Utilizing Silicon Technology," presented at and published in The Proceedings of the SPIE Meeting, Cambridge, Massachusetts, October, 1984.

J.T. Boyd, A. Naumaan, R.W. Wu, and D.E. Zelmon, "Integrated Optical Devices Utilizing Silicon," presented at and published in The Proceedings of the 1984 National Science Foundation Grantee-User Meeting on Optical Communications, University of California at San Diego, June, 1984.

J.T. Boyd, H.E. Jackson, D.E. Zelmon, and P.B. Kosel, "Optical Waveguide Structures Utilizing Silicon Substrates," presented at and published in The Proceedings of the 1983 National Science Foundation Grantee-User Meeting on Optical Communications, Massachusetts Institute of Technology, June, 1983.

H.E. Jackson, D.E. Zelmon, J.T. Boyd, and P.B. Kosel, "Fabrication of a Graded-Index SiO_2 Planar Optical Waveguide on Silicon Exhibiting Low Scattering," presented at and published in The Proceedings of the Society of Photoinstrumentation Engineers Meeting, Arlington, Virginia, April, 1983.

J.T. Boyd, "Microfabrication Techniques for Integrated Optics," presented at and published in The Proceedings of Electro/83, New York, April, 1983.

J.T. Boyd, "Past Progress and Future Directions of Research on Optical Waveguide Structures Formed on Silicon Substrates," presented at and published in The Proceedings of the 1982 National Science Foundation Grantee-User Meeting on Optical Communications, Berkeley, June, 1982.

S. Dutta, H.E. Jackson, and J.T. Boyd, "Use of Laser Annealing to Achieve Low Loss in Corning 7059 Glass, ZnO, Si_3N_4, Nb_2O_5, and Ta_2O_5 Optical Thin-Film Waveguides", presented at and published in The Proceedings of the Society of Photoinstrumentation Engineers Meeting, Los Angeles, January, 1982.

Conference Presentations Without Written Proceedings

D.E. Zelmon, J.T. Boyd, and H.E. Jackson, "Low Loss Planar Optical Waveguides Fabricated on Silicon," to be presented at the Midwest Symposium on Circuits and Systems, Louisville, Kentucky, August, 1985.

H.E. Lu, R.W. Wu, J.T. Boyd, and J.L. Janning, "A CMOS Test Circuit Formed on Laser Recrystallized Silicon-On-Insulator", presented at the Joint Spring Meeting of the Ohio Section of the American Physical Society and the Southern Ohio Section of the American Association of Physics Teachers, University of Cincinnati, Cincinnati, Ohio, April 12-13, 1985.

S.M. Chen, J.T. Boyd, and H.E. Jackson, "Integrated Optics on $LiNbO_3$", presented at the Joint Spring Meeting of the Ohio Section of the American Physical Society and the Southern Ohio Section of the American Association of Physics Teachers, University of Cincinnati, Cincinnati, Ohio, April 12-13, 1985.

S. Dasgupta, H.E. Jackson, and J.T. Boyd, "Laser Recrystallization of Si on SiO_2 by Ar^+ and CO_2 Laser Irradiation", presented at the Joint Spring Meeting of the Ohio Section of the American Physical Society and the Southern Ohio Section of the American Association of Physics Teachers, University of Cincinnati, Cincinnati, Ohio, April 12-13, 1985.

J.T. Boyd, "Fabrication of Electronic Devices Using Laser Recrystallized Silicon," presented at the Tri-State Symposium on Laser Applications, Cincinnati, April, 1985.

S. Dasgupta, H.E. Jackson, and J.T. Boyd, "Two Beam Laser Recrystallization of Silicon on an Insulating Substrate," presented at The American Physical Society Meeting, March, 1985.

J.T. Boyd, D.E. Zelmon, H.E. Jackson, and P.B. Kosel, "Properties of Graded-Index SiO_2 Planar Optical Waveguides," presented at the Meeting of the Optical Society of American, New Orleans, October, 1983.

S. Dutta, J.T. Boyd, and H.E. Jackson, "Laser Annealing of ZnO Optical Waveguides," presented at the Meeting of the American Physical Society, Dallas, March, 1982.

J.T. Boyd, "Laser Annealing of Semiconductor and Optical Materials," presented at the Tri-State Symposium on Laser Applications, Cincinnati, May, 1981.

Ph.D. Dissertations

A. Naumaan, "Phosphosilicate Glass For Integrated Optics," Ph.D. Dissertation, University of Cincinnati, 1985.

R.W. Wu, "Optical Waveguide Detection: Photodetector Array Formed on the Waveguide Utilizing Laser Recrystallization Silicon-On-Insulator Technology," Ph.D. Dissertation, University of Cincinnati, 1984.

S.H. Chang, "Log-Converting CCD Sensor Element and Three-Gate MOSFET Device," Ph.D. Dissertation, University of Cincinnati, 1983.

C.L. Fan, "Improvement in the Performance of Silicon Photodetectors Used in Integrated Optics by Edge Illumination and Optical Waveguide Integration," Ph.D. Dissertation, University of Cincinnati, 1983.

S. Dutta, "Reduction of Scattering in Thin-Film Optical Waveguides by Carbon Dioxide Laser Annealing," Ph.D. Dissertation, University of Cincinnati, 1981.

M.S. Theses

H.A. Timlin, "Laser Recrystallization of Silicon-on-Insulator," M.S. Thesis, University of Cincinnati, 1984.

H.S.E. Lu, "CO_2 Laser Annealing of SiO_2 and Laser Recrystallization of Polysilicon or Insulator," M.S. Thesis, University of Cincinnati, 1983.

D.E. Zelmon, "A Planar Graded-Index SiO_2 Waveguide," M.S. Thesis, University of Cincinnati, 1983.

VII. Acknowledgements

The authors wish to acknowledge contribution from several others not isted as authors, but who contributed to the research described herein. In particular, Dr. Robert W. Wu carried out the integration of photodetectors onto optical waveguides, H. A. Timlin created the experimental configuration for laser recrystallization and performed many of the early experiments on laser recrystallization, Dr. Ahmed Naumaan perfored the ring resonator fabrication and experiments, David E. Zelmon perfored the research on SiO_2 waveguides, Dr. S. H. Cheng performed the research on the log-converting image sensor and three-gate MOSFET, Dr. C. L. Fan performed the experiments on edge illumination to enhance quantum efficiency, and Dr. Joseph H. Nevin participated in three-gate MOSFET research. In addition M. Biedenbender and G. Valco performed the Auger measurements described. The technical assistance of James T. Garrett and Roger A. Kirschner in performing a variety of specialized tasks is appreciated.

Suggestions and constructive comments from discussions with the program monitor, Lieutenant Colonel Robert Carter, are also appreciated.

VIII. References

1. R.W. Wu, J.T.Boyd, H.A. Timlin, H.E. Jackson, and J.L. Janning, "Optical Waveguide Detection: Photodetector Array Formed on the Waveguide Utilizing Laser Recrystallized Silicon," Applied Physics Letters 46, 498, 1985.

2. R.W. Wu, H.A. Timlin, H.E. Jackson, and J.T. Boyd, "Photodetector Arrays in Laser Recrystallized Silicon Integrated with an Optical Waveguide," presented at and published in The Proceedings of the Materials Research Society Meeting, Boston, November, 1984.

3. D.E. Zelmon, J.T. Boyd, and H.E. Jackson "Low Loss Optical Waveguides Fabricated by Thermal Nitridation," Applied Physics Letters 47, 353, 1985.

4. D.E. Zelmon, H.E. Jackson, and J.T. Boyd, "Use of Thermal Nitridation to Fabricate Low Loss Planar Optical Waveguides in SiO_2," presented at and published in the Proceedings of the Second SPIE International Conference on Integrated Optical Circuit Engineering, Cambridge, MA, September, 1985.

5. A. Naumaan and J.T. Boyd, "Ring Resonator Fabricated in Phosphosilicate Glass Films Deposited by Chemical Vapor Deposition," to be published.

6. C.L. Fan and J.T. Boyd, "Improvement in the Quantum Efficiency of Silicon Photodetectors at Near IR Wavelengths by Edge Illumination," Applied Optics 22, 3297, 1983.

7. S.H. Chang and J.T. Boyd, "Log-Converting Processor Element For CCD Linear Imaging Arrays," Applied Optics, Vol. 22, pp. 3569-3571, 1983.

8. S.H. Chang, J.T. Boyd, and J.H. Nevin, "Three Gate MOSFET Providing Independent Control of Transconductance and Output Resistance," IEEE Electron Device Letters, Vol. EDL-4, pp. 289-291, 1983.

9. D.A. Ramey and J.T. Boyd, "Polyurethane Fan-Out Channel Waveguide Array For High Resolution Optical Waveguide Imaging," IEEE Trans. on Circuits and Systems, Special Issue on Optical Circuits and Systems, Volume CAS-26, pp. 1041-1048, 1979.

10. J.T. Boyd, D.A. Ramey, and C.L. Fan, "Enhanced Optical Waveguide Focal Plane Resolution Utilizing a Channel Waveguide Fan-Out Array Coupled to an Integrated CCD," presented at and published in The Proceedings of the Fifth International Conference on Charge-Coupled Devices, Edinburgh, Scotland, September 12-14, 1979.

11. J.P. Colinge, E. Demoulin, D. Bensahel, and G. Auvert, "Use of Selective Annealing for growing Very Large Grain Silicon on Insulator Films," Applied Physics Letters 41, 346, 1982.

12. G.E.J. Eggermont and J.G. deGroot, "Diode Characteristics in Laser Recrystallized and Conventional Polycrystalline Silicon," IEEE Electron Device Letters EDL-3, 156, 1982.

13. D.E. Zelmon, H.E. Jackson, J.T. Boyd, A. Naumaan, and D.B. Anderson, "A Low-Scattering Graded-Index SiO_2 Planar Optical Waveguide Thermally Grown on Silicon," Applied Physics Letters, Vol. 42, pp. 565-566, April 1, 1983.

14. J.T. Boyd, R.W. Wu, D.E. Zelmon, A. Naumaan, H.A. Timlin, and H.E. Jackson, "Guided Wave Optical Structures Utilizing Silicon," Optical Engineering, Special Issue on Integrated Optical Circuit Engineering, Vol. 24, pp. 230-234, 1985.

15. A. Naumaan, "Phosphosilicate Glass For Integrated Optics," Ph.D. Dissertation, University of Cincinnati, 1985.

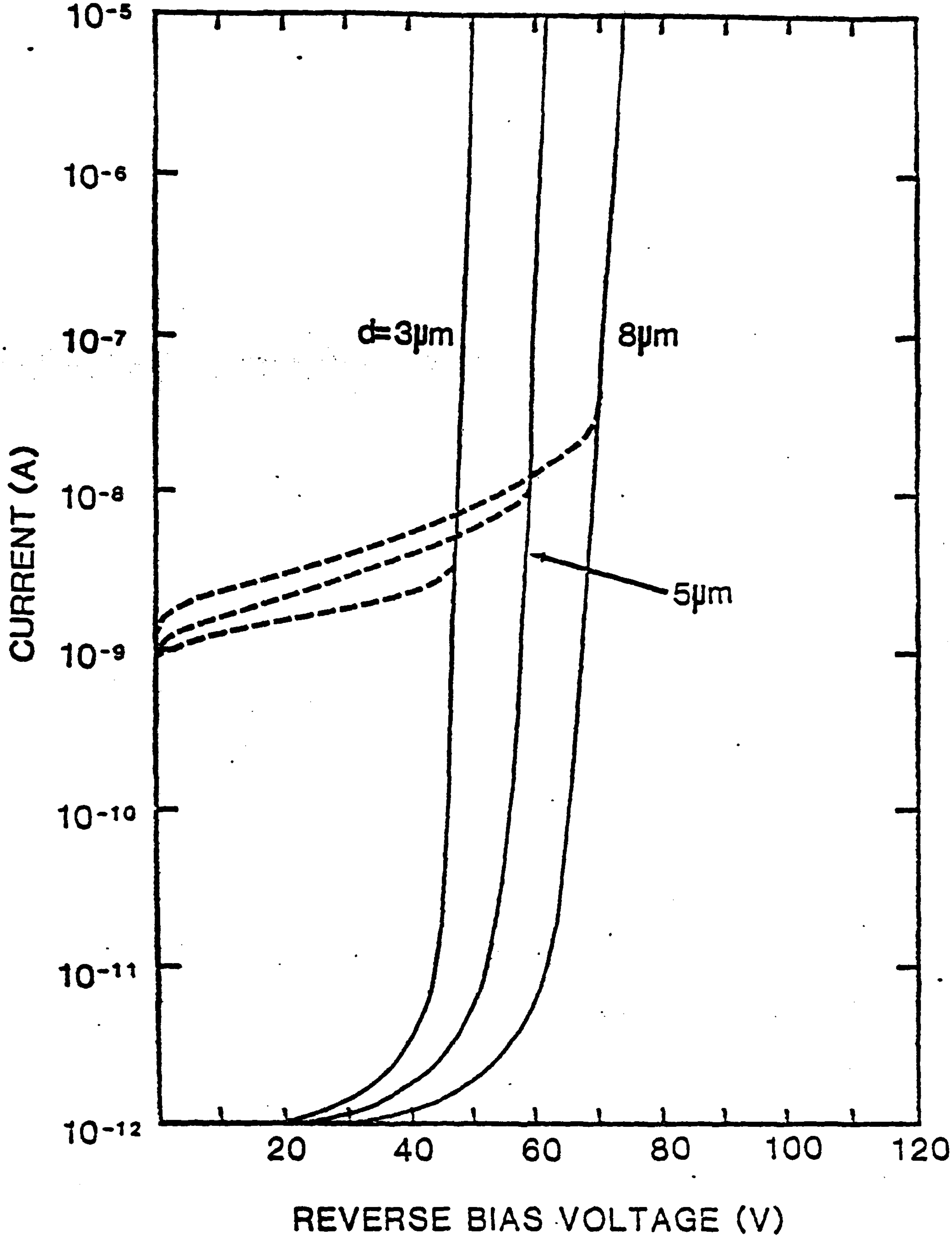


Figure 3 Current-voltage characteristics of an element of the photodetector array formed on recrystallized silicon with light propagating in the waveguide (dashed curves) and without light propagating in the waveguide (solid curves). Detection of light from the waveguide provides a photocurrent response of 3-4 orders of magnitude for a input He-Ne laser power of 4 mW.

END

DTIC

5-86